Effect of Nuclear Shallow Burst on Asteroids

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The effect of the nuclear explosion on the asteroid will be the most intensive, if the nuclear explosive device is buried into the asteroid ground before the explosion. This is associated with the fact, that at such type of explosion (unlike the surface and the stand-off explosions) the explosion energy at the initial stage of the process is entirely transferred to the asteroid ground. As the result the effect of the buried explosion on the asteroid is equivalent to the effect of the surface explosion with the yield tens of times greater [1]. Therefore, consideration of the buried explosion effect on the asteroids is of peculiar interest.

In this paper we consider the problem of the effect of the nuclear buried explosions on the stony asteroid (as the most wide-spread type of the NEOs). On the basis of numerical modeling of nuclear shallow bursts in the dense crushable medium we studied some regularities of their effects as a function of the depth -of-burst.

Some results of calculating the explosions in granite at the scaled depth of 1, 2, 3, and 15 m/kt$^{1/3}$ are given. Configurations of the calculated destruction zones and dependences of the shock amplitude decrease upon the depth are given . The change in the effect intensity with increase of the explosion depth is illustrated on the basis of calculated values of energy withdrawn by the elastic wave.

The possibility of schematizing the phenomenon by using the concept of the explosion equivalence at different scaled depth is discussed. This concept facilitates the process of taking the engineering decisions using the numerical simulation results. The limits of the equivalent explosion concept applicability are illustrated on the basis of the calculations.

The numerical modeling was carried out using the complex of codes called "SD-TOM". The mathematical formulation of the problem is considered. Some characteristics of the medium model and the difference method are given.

Introduction

The effect of the nuclear explosion on the asteroid will be the most intensive, if the nuclear explosive device is buried into the asteroid ground before the explosion. This is associated with the fact, that at such type of explosion (unlike the surface and the stand-off explosions) the explosion energy at the initial stage of the process is entirely transferred to the asteroid ground. As the result the effect of the buried explosion on the asteroid is equivalent to the effect of the surface explosion with the yield tens of times greater [1]. Therefore, consideration of buried explosion effect on the asteroids is of peculiar interest.

If time till the assumed asteroid encounter with the Earth is small (~1 year) the response must be organized under conditions of the minimum warning time. In this case to provide the required change of the asteroid trajectory we need to transfer to it a rather large momentum using the explosion of appropriate yield. As the assessments show [1] for the given asteroid dimensions to transfer the necessary momentum we need the explosion of such yield that the destruction zone will be commensurable with the asteroid dimensions. Thus, the effect on the asteroid will be reduced not to altering its orbit, but to the asteroid disintegration into separate fragments. These fragments will scatter in space at velocities significantly higher than change of the asteroid mass center velocity caused by the explosion. Some part of the asteroid fragments will pass by the Earth, and the remaining part with appropriate dimensions will burn in the Earth atmosphere at a large distance from one another without causing any damage.

The experimental data show [2] that the ground fragmentation in direct shock wave of the nuclear explosion proceeds very intensively, and maximum dimensions of the fragments (~5 m) are significantly less than the critical dimensions (~30 m) at which the complete burning in the atmosphere is provided. However, if the asteroid dimensions to some extent exceed dimensions of the fragmentation zone, the fragments with dimensions exceeding the critical one may be formed. Impact of such fragments into the Earth may cause hazardous consequences, though essentially less severe than in the case of the not destroyed asteroid impact.

Due to the spall phenomena during propagation of the rarefaction wave from the back side of the asteroid dimensions of the fragmentation zone during the explosion at the asteroid of appropriate diameter exceed dimensions of the fragmentation zone in the case of the explosion near the semispace surface. Therefore, from the engineering standpoint to achieve the guaranteed disintegration of the asteroid into the fragments it is sufficient to affect the asteroid with the explosion of such yield and at such depth as to provide exceeding of the fragmentation zone dimensions at the same explosion near the surface of semispace over the asteroid dimensions. It should be pointed out that we don't consider the problem of destroying the asteroid of complex shape, e.g., looking like a long galosh. For such asteroids we'll need to use several simultaneous explosions if it is technically feasible. In the opposite case the necessary effect is achievable only by several simultaneous surface explosions (that is also technically difficult), or by the stand-off explosion of high yield. We believe it is possible to perform consecutive explosions if time interval between them is large enough.

Thus, we are faced with the problem of determining dimensions of the fragmentation zone at the buried explosion near the semispace surface. This paper is primarily dedicated to consideration of this problem.

Description of the Problem

The main increase of intensity of acting on the asteroid during transition from the surface explosion to the buried explosion is observed at the depth-of-burst (DOB) up to 0.2 m/kt$^{1/3}$. This is associated with increase of the explosion energy fraction transferred to the ground at the initial phase, when the processes of energy transfer by radiation are considerable, from less than 10% up to 100% [1]. During subsequent increase of the explosion depth the growth of the effect intensity is significantly less, and is associated with increase of the depth at which the rarefaction wave from the free surface will overtake the shock propagating in the ground.

On the other hand, the actually achievable values of the DOB make up from several meters up to several tens of meters. Therefore, assuming that for the asteroid destruction by the buried explosion we'll use the nuclear devices having yield of ~1 Mt, below we consider the explosions with the DOB 1,2,3 m/kt$^{1/3}$. The main task of the calculations was to determine configuration of the fragmentation zones at such explosions in the uniform semispace.

It is known [3] that the gasdynamic flows formed during the explosion even with account for many elastic-plastic and strength effects possess similarity. Namely, there is a characteristic dimension - dynamic radius $r_d = (E/\rho_0 c_0^2)^{1/3}$ characterizing the explosion scale, and generally speaking, the characteristic radius of the energy dissipation (for rocks $r_d \approx 4...5$ m/kt$^{1/3}$). In this expression E is the explosion yield, ρ_o is characteristic density of the ground, c_o is characteristic sound velocity in the ground. While considering some class of the grounds rather similar in terms of their properties, the term containing the density and sound velocity can be dropped. Therefore, in particular, the flows formed during the buried explosions of different yield at the same scaled depth $\overline{H} = H/E^{1/3}$, exceeding 0.2 m/kt$^{1/3}$ will be similar for the given class of the grounds. If the explosion depth is significantly less than the dynamic radius, we might expect that with the shock propagation in the ground the details of the initial source will be "forgotten", and at some distance from the centers of the explosions the flows will turn to be also quasi-similar. This allows us to introduce a notion of the explosion equivalency [4] very convenient to generalize the results of the calculations and engineered applications. That is, in this case the explosion with the yield E_1 at the scaled depth $\overline{H}_1$ will at some distance significantly exceeding the depth of the explosion create the same flow field, as the explosion having yield $E_0 = \eta(\overline{H}_1) \cdot E_1$ at the scaled depth $\overline{H}_0$. The coefficient of equivalence η characterizes change of the effect intensity with increase of the explosion scaled depth.

The second problem we were considering was assessing feasibility of using the principle of the buried explosion equivalence, and determining limits for applicability of this principle. Therefore, we also computed the explosion at the scaled depth 15 m/kt$^{1/3}$.

Calculations: Model of Medium

Numerical simulation of the buried explosions was done using the complex of codes called "SD-TOM". As a ground we took a rock which was described by one of the models which have been widely considered in literature in association with study of mechanical effects of powerful underground explosions [5]-[8]. The medium parameters were selected to simulate the results given, e.g., in [12] for explosion in granite.

To carry out the calculations were made a number of assumptions:

1. The two-dimensional calculation started from the moment when the shock reached the free surface. During that as initial conditions we used results of one-dimensional calculation by other authors obtained in gasdynamic approximation taking into account the energy transfer in approximation of radiant heat conductivity.
2. To simulate behavior of the material evaporated in the shock we used the equation of state of the type of Mi-Gruneisen with transition to the ideal gas at compression less than 1.
3. To simulate behavior of the scattering destroyed ground in the case of its essential decondensation and mixing with the evaporated ground we used the same equation of state as for the evaporated ground.
4. Periodically, when pressure in remote part of the cloud reduced by several orders this region was omitted from the calculation.
5. Gravity influence was not taken into account.

Some remarks on the used model of the crushable medium.

The medium element is considered as a totality of the matter and voids (fractures, pores). Specific volumes of the matter V_m and the voids V_n are determined during the calculations.

The tensor of stress in the medium element is determined by the tensor of stress in the matter.

The spherical part of the tensor of stress in the matter (pressure) is determined by equation of state of the type $p = p(V_m, e_1)$, where e_1 is internal energy which doesn't include the work of the stress deviator at the elastic shear. In the calculations we used the equation of state of the Mi-Gruneisen's type.

In the directions where the medium strength was preserved the components of the tensor-stress-deviator are related to the components of the tensor of the strain rates through the Hooke's law.

Rock possesses breaking strength and shearing strength. The rock weakened by the fractures of any directions possesses less strength.

Material destruction during extension occurs when the maximum extending stress exceeds the breaking strength limit (σ_{cr}). At the moment of the fracture opening in the medium element the stress orthogonal to the fracture surface is assumed to be zero until the complete closure of the fractures of this direction. Deformations of matter in the directions corresponding to the strong state of the medium are considered to be coinciding with the medium strains. When the medium element turns like a solid body the fractures turn together with it.

As a criterion of the medium destruction during the shearing the generalized condition of Hubert-Mises is used. If this criterion is not met the medium looses strength in all the directions.

In the completely destroyed medium the components of the tensor-stress-deviator are related to the components of the tensor of the strain rates through the law of flow of Prandtl-Reiss with the yield limit proportional to pressure.

The Difference Method

The complex of codes SD-TOM is intended for computing two-dimensional non-stationary motions of compressible media taking into account the strength effects and the elastic-plastic properties. The calculation is done by the regions, each region has its own regular quadrangular mesh. Boundaries of the calculation region do not necessarily coincide with the substance interfaces. Each calculation region may have several substances, but the calculation cell must have not more than three.

The main equations are written with account for the tensor properties of the medium. For simultaneous solution of the equations of hydrodynamics and elastic-plastics the SD-TOM uses explicit method which has elements of several known difference setups. Lagrangian and Lagrangian-Eulerian description is allowed. At the Lagrangian phase the equations of energy and elastic-plastics are solved as in the program "SPRUT" [8], the equations of motion - as in [10]. In the zones of large strains the Lagrangian-Eulerian description is used, where at the second phase the meshes are reformulated, and the quantities are transferred to the new meshes. In the case of small change in the meshes to transfer the quantities we use the method accounting for the convectional flows through the cell borders [11]. In the case of considerable change we use the method of "fractional design" based on [12]. If the substance interface doesn't coincide with the mesh lines it is described approximately using the method of "concentrations" and the special algorithm preventing excessive diffusion of substances during the mesh reconfiguration, analogously to [10].

Calculation Results and Discussion

Configurations of the destruction zones obtained in the numerical calculations are shown in figure 1.

The numerical calculations showed that the principle of equivalence is applicable to explosions with the scaled DOB at least, up to 3 $m/kt^{1/3}$. To illustrate this figure 1 shows isobars for the explosions with the DOB 1 and 3 m/kt$^{1/3}$. Change of the shock intensity with the distance along the axis of symmetry in the direction from the free surface for 15 m/kt$^{1/3}$<r< 150 m/kt$^{1/3}$ at good accuracy can be presented in the form $p = A(\overline{H}) \cdot (r/E^{1/3})^{-1.62}$. Calculation of the explosion at the depth 15 m/kt$^{1/3}$ showed that the principle of equivalence is violated for such depths.

We can understand the character of the dependence of equivalence coefficient $\eta(\overline{H})$ if, e.g., we consider the fraction of energy withdrawn by the elastic wave. This energy E_s can be estimated by the work A_s at the boundaries lying within the region of applicability of the theory of elasticity where the destruction is absent, and the compression is not large, i.e. the energy dissipation is absent. For the contained explosions the boundary of this region has the radius r_s>100...150 m/kt$^{1/3}$. While comparing the shallow-burried explosions we should consider work at the boundaries the distance to which is proportional to $\eta(\overline{H})^{1/3}$. It should be pointed out that accurate determination of E_s/E is difficult in our calculations since time of the elastic wave formation is much larger than the characteristic explosion time. The calculated values of A_s/E are given in Table 1.

Table 1. Dependence of the work A_s at the boundary r_s upon the DOB

$\overline{H}$, m/kt$^{1/3}$	r_s, / kt$^{1/3}$	A_s/E
15	200	0.0111
3	183	0.0086
2	160	0.0056
1	137	0.0036

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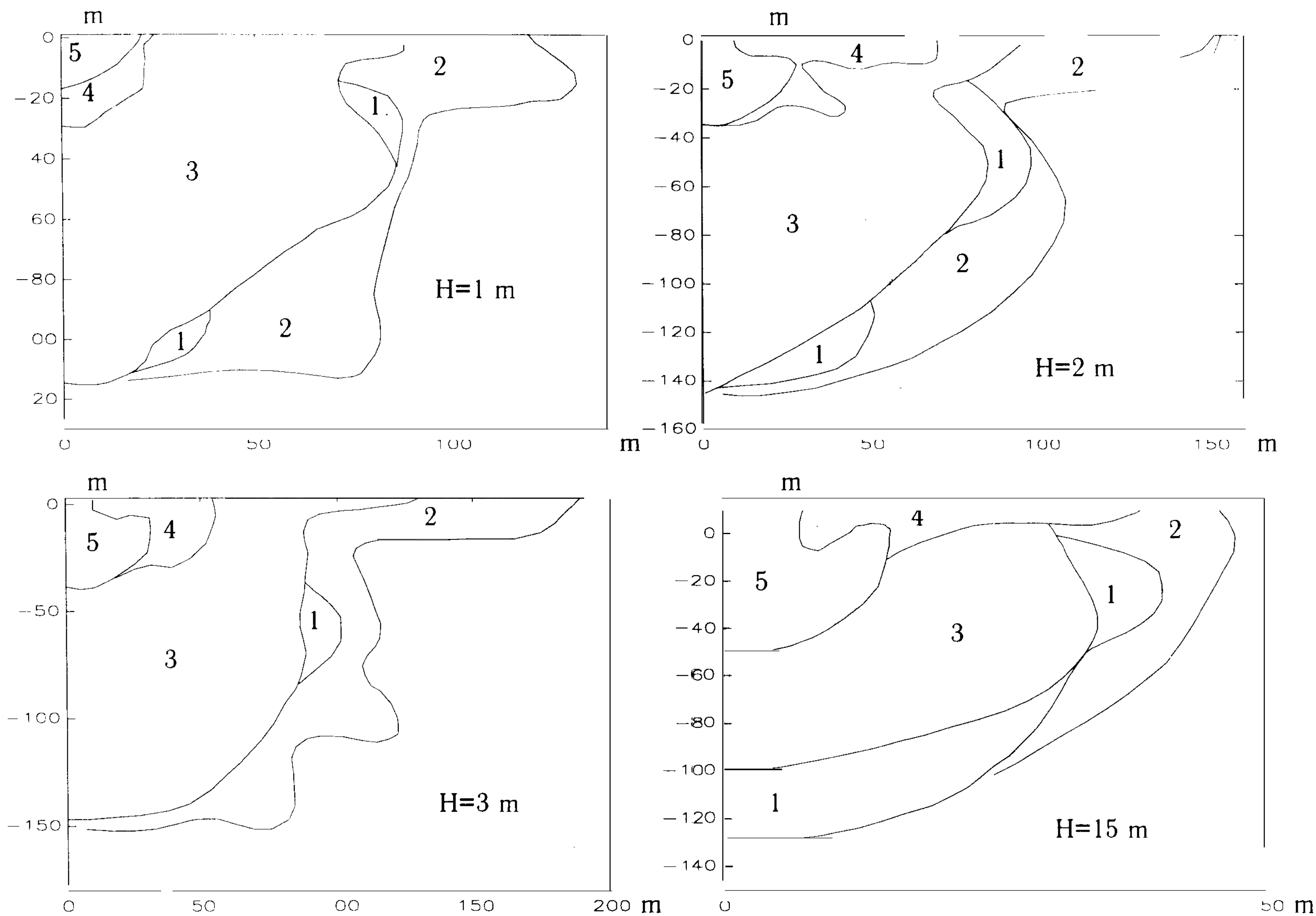

Figure . Configuration of he destruction zones.

Figure 1. Configuration of the destruction zones.

"1" - the fractures of family "1" - the surfaces repeating the front of rarefaction wave (spherical surfaces in the case of spherical symmetry);

"2" - the fractures of family "2" - the surfaces ortoganal to the front of rarefaction wave (radial fractures in the case of spherical symmetry);

"3" - the fractures of two families - "1" and "2";

"4" - the fractures of three families ("1" and "2") - the material is comletely crushed under stretching;

"5" - the material is comletely crushed by shock wave (under compression).

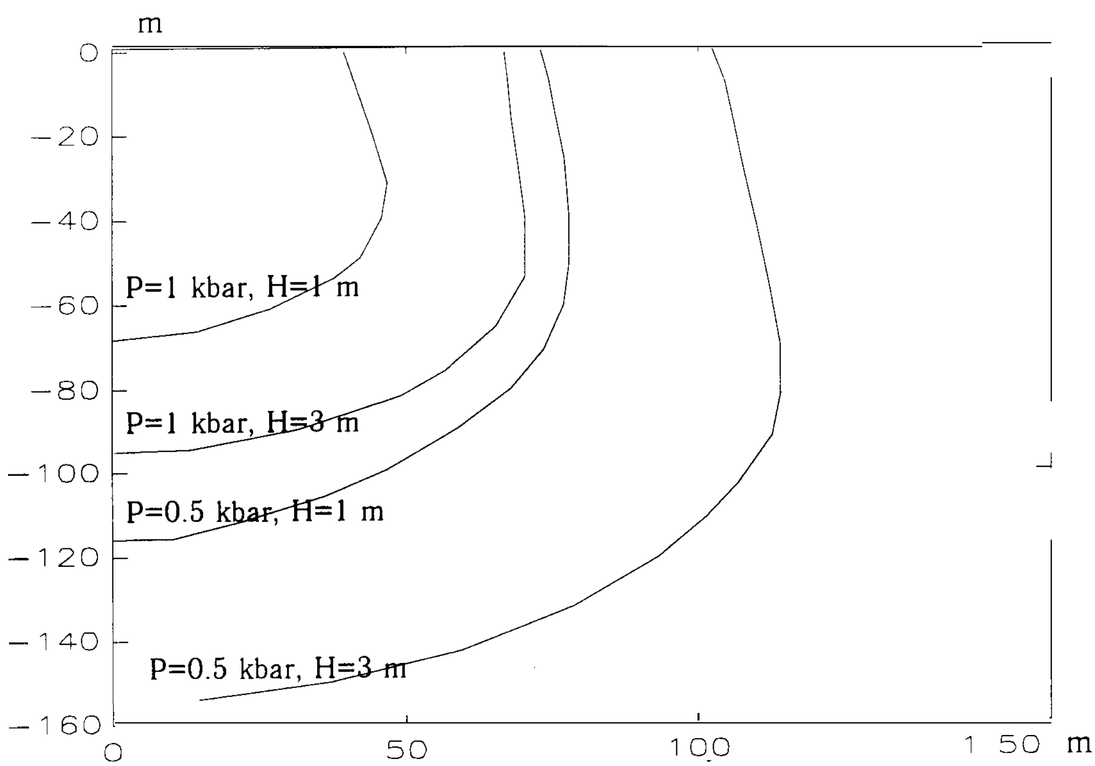

Figure 2. Peak stresses isobars